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SUBMILLIMETRE LASER, MICROWAVE AND SPECTROSCOPIC DIAGNOSTICS OF IONIZATION IN GASEOUS PLASMAS

Final Scientific Report

1 June 1972 - 30 June 1976

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and

European Office of Aerospace Research and Development, London,England

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Submillimetre laser; plasma afterglows; microwave noise

20. Abstract

Afterglow electron density decay mechanisms and energy losses in high energy argon and helium plasmas including measurements of ion conversion rates were carried out. A computational study of the hydrogen and helium afterglows was also completed.

Development of a HCN submillimetre laser included work on the significance of mode compression near the critical density.

Microwave electron temperature measurements in a current modulated plasma column were also undertaken.

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CONTENTS

INTRODUCTION

During the period covered by this report four distinct types of related projects were in progress in this laboratory, involving the interaction of electromagnetic radiation with plasmas. They were:

(a) Electron temperature variations in a current modulated plasma column.

(b) Afterglow electron density decay mechanisms and energy losses in high energy argon and helium plasmas, including measurements of ion conversion rates.

(c) Computational study of highly ionized plasmas involving a one-dimensional code for the simulation of hydrogen and helium afterglows.

(d) Generation and detection of far infrared (submillimetre radiation using a HCN gas laser and semiconductor detectors.

Since most of this work has already been or is in the course of publication in journals or conference proceedings, this report will summarise the research by means of abstracts of the papers, augmented by more detailed descriptions where necessary.

THE VARIATION OF ELECTRON TEMPERATURE IN PLASMA COLUMNS

The method involved the design of a sensitive 11.5 GHz microwave radiometer and is fully described in the following papers:

1) An electronically switched microwave radiometer
C.J.Burkley, C.P.Downing and M.C.Sexton
J.Phys.D (Appl.Phys), 6, 668, 1973

Abstract:

An 11.5 GHz microwave radiometer is described in which periodic noise variations up to 1 kHz were resolved by a sampling process using PIN diode switching.A sensitivity of 0.04 dB (100 °K) was recorded in checking the system with the noise power emanating from a current-modulated plasma column.

2) Electron temperature variations in deeply modulated plasma columns
C.J.Burkley, and M.C.Sexton
Bulletin of Am.Phys.Soc. 18,807,1973
(Presented at 25th Annual Gaseous Electronics Conf., London,Ontario,17-20 October 1972)

Abstract:

An 11.5 GHz microwave radiometer was used to monitor electron temperature variations in argon and krypton plasma columns by means of a sampling process involving PIN diode switching. Temperature variations as low as 0.04 dB (100°K) were recorded in 0.5A columns current modulated up to 85% with sinusoidal and triangular waveforms.

3) Electron temperature measurements in a current modulated plasma column

C.J.Burkley, D.M.Barry and M.C.Sexton
Proc.11th Int.Conf.on ion phenomena in gases,Prague, September 1973, p.42.

Abstract:

The measurement of electron temperature in the positive column of a gas discharge was carried out by monitoring the microwave noise radiation with a sensitive 11.5 GHz radiometer using Schottky barrier mixer diodes. PIN diode switching was introduced to enable the noise radiation from the discharge to be compared with a calibrated noise source under current modulated (sine and triangular) conditions in the positive column.
In argon and krypton plasmas and with mean currents of approximately 0.5A,the modulation was shown to produce a "hysteresis" effect in the current/temperature relation. This was ascribed to differing electron radial distribution for increasing and decreasing modulation currents.

A feature of this work (which has now terminated - see Interim Scientific Report No.2,p.1) is that although the radiometer performance was checked with a modulated plasma only,it can be applied to any system in which rapid power fluctuations are likely to occur, e g., fading on microwave radio links.

AFTERGLOW DECAY MECHANISMS

(a) Electron density measurements and afterglow thermal economy:

The design and construction of a Hydrogen Cyanide (HCN) laser which operates at 890 GHz (337μM) and a submillimetre interferometer with an 8 millimetre microwave bridge which together measure electron densities in the range 7×10^{14} cm^{-3} to 8×10^{11} cm^{-3} in the afterglow of pulsed helium and argon discharges was described. Electron temperature measurements were made on both gases with a monochromator-photomultiplier system.

Recombination coefficients were extracted from the electron density decay curves and these indicated the dominance of collisional radiative recombination in both gases. In helium the electron temperature dropped from 7000^{o}K to less than 3000^{o}K in 0.6 msec, while the recombination coefficient varied from almost 10^{-9} cm^3 sec^{-1} to 7×10^{-11} cm^3 sec^{-1} over the electron density range 3×10^{12} cm^{-3} to 5×10^{14} cm^{-3}. A comparison of these results with previous experimental work on helium showed good agreement. The effect of including an elevated and time-varying neutral gas temperature in the calculations involving ion-atom energy exchange brought theoretical predictions and the present experimental results into excellent agreement.

The measured values of electron temperature in argon were much higher than in helium,dropping from over 16,000 ^{o}K to 8,000 ^{o}K in 0.35 msec. The experimentally determined values of recombination coefficient varied from 1.6×10^{-9} cm^3 sec^{-1} to 1.54×10^{-11} cm^3 sec^{-1} over the electron density range 8.25×10^{11} cm^{-3} to 3.6×10^{14} cm^{-3}. These results compared very favourably with previous experimentally determined values. In the calculations,the effects of optical transparency to plasma radiation were also included.

Papers:

4) Afterglow decay processes in highly ionized helium and argon plasmas
J.H.Mountjoy and M.C.Sexton
Bull.Am.Phys.Soc. 19,159,1974
(Presented at 26th Gaseous Electronics Conf., Madison,Wis. October 1973)

Abstract:

A HCN laser interferometer was used to monitor electron densities from 10^{15} to 10^{12} cm^{-3} in He and Ar afterglows in which electron and neutral gas temperatures were also monitored. Binary electron-atom (collisional) recombination was clearly identified as the principal decay mechanism,with coefficients within the range 10^{-9} to 10^{-11} cm^3 sec^{-1}. Excellent agreement with theory was obtained by including elevated and time-varying gas temperatures into the calculations.

(b) Ion conversion in high density afterglows

A free space microwave interferometer was used to monitor the decaying electron density afterglows of argon and helium plasmas pulsed by varying d.c.voltages. The formation of the molecular ion Ar_2^+ was found to depend on the input power - a result not previously reported - which should have significance for developments in high power rare gas lasers.

In the present work the experimental parameters were as follows:

Microwave probing frequency:	35 GHz (cut-off density $\approx 10^{13}$ cm^{-3}
Maximum discharge conditions (variable):	20kV, 5kA for 20μs
Discharge tube diameter:	10.2 cm (internal)

argon at 0.3 - 1 torr
helium at 1 - 6 torr

The basic reaction for atomic to molecular ion conversion during an afterglow is

$$X^+ + X + X \rightarrow X_2^+ + X$$

where the second atom X, i.e. the third body,carries off the excess energy and accordingly stabilises the reaction. Clearly the reaction is a function of pressure and since electron recombination to atomic ions (X^+) is considerably less than that to molecular ions (X_2^+) a rapid decrease in the afterglow electron decay time occurs if the reaction occurs during increase of neutral gas pressure.

Paper

5) Ion conversion rates in the afterglows of high power argon plasmas

P.J.Murphy and M.C.Sexton
Bull.Am.Phys.Soc. 20,256,1975
(Presented at 27th Gaseous Electronics Conf.,Houston, Texas, October 1974)

The dependence of the reaction rate constant k for the process $Ar^+ + 2Ar \rightarrow Ar_2^+ + Ar$ was examined with a 35 GHz microwave interferometer over the electron density range 10^{13} - 10^{11} cm^{-3} in argon afterglows. The value of k varied from 2.9 to 1.5 x 10^{-31} cm^6 sec^{-1} as the input power increased from 15 to 350 mJ cm^{-3}. Moreover,the gas pressure at which the onset of the conversion process occurred increased during the same range of input power.

Similar results in helium gave k decreasing from $3.5 - 1.4 \times 10^{-32}$ cm^6 sec^{-1} as the electron temperature varied from 350 ^{o}K - 1300 ^{o}K.

Both the afterglow and ion conversion work described in this section have now been concluded.

COMPUTATIONAL STUDY OF HIGHLY-IONIZED PLASMA AFTERGLOWS

Throughout the experimental afterglow work described above, computer simulation studies (Glowcode) were initiated in collaboration with the Culham Laboratory (Euratom/UKAEA Fusion Association) and Oxford Polytechnic. The GLOWCODE program simulates the behaviour of an afterglow plasma in one-dimensional cylindrical geometry and its purpose is to study and clarify the various competing processes taking place in an afterglow in which inertial effects may be neglected. The numerical model predicts the radial and temporal distributions of a three fluid plasma comprised of positive ions,neutral atoms and electrons. Thus the afterglow is described by the dependent variables n_e, n_i, n_a, T_e, T_i, T_a which represent the electron, ion and atom densities and the electron,ion and atom temperatures respectively.

For computational purposes the plasma consists of a nesting set of cylindrical shells,each shell characterised by its mean radius and its thickness.The calculation proceeds by calculating the energy changes due to the various collisional and radiative processes in each shell, and the transport between neighbouring shells. At each stage of the calculation pressure balance is restored by adjustment of the cylindrical shells until the total particle pressure gradient is zero everywhere. Since the plasma is subject to a continual radial motion it is convenient to express the various physical equations in Lagrangian form.

The code is structured within the OLYMPUS package introduced by Christiansen and Roberts (Com. Phys.Comm. 7,245,1974). Using this system it is possible for the user to make ad hoc changes to the program using the EXPERT facility so that,for example,different rate coefficients could be prescribed for a particular physical process. Alternatively,a particular physical process may be suppressed,which is useful when one is studying the relative importance of the various competing processes.

Paper: GLOWCODE: a one dimensional code for the simulation of plasma afterglows

J.W.Long, A.A.Newton and M.C.Sexton
Com.Phys.Comm. 9,1976 (accepted for publication)

This is a comprehensive paper,the main features of which are abstracted above. The computational details are as follows.

Title of Program: GLOWCODE

Program obtainable from: CPC Program Library,Queen's University of Belfast,N.Ireland

Computer: ICL System 4: Installation:Culham Laboratory

Operating System: Multijob

Programming language used: STANDARD FORTRAN

No.of bits in a word: 32

High Speed Store required: 24000 words

Overlay Structure: None

No.of Magnetic Tapes required: None

Other peripherals used: Line printer

No.of cards in combined program and test deck: 2487

Card punching code: EBCDIC

CPC Library Subprograms used: Catalogue No: Title
ABUF OLYMPUS
Ref.in CPC:
7(1974)245

Keywords: Afterglow,ionisation,recombination,diffusion, implicit,Lagrangian.

Following the setting up of the program theoretical studies were carried out on hydrogen and helium afterglows.

7) Computational study of highly ionized plasma afterglows:
J.W.Long, A.A.Newton and M.C.Sexton
1st Europhysics Study Conf.on Atomic and Molecular Physics of Ionized Gases, Versailles,April 1973, Paper F6.

Results are presented for the hydrogen afterglow with the following parameters:

Electron density	:	10^{16} - 10^{14} cm^{-3}
Afterglow period	:	0 - 100 μsec
Gas pressure	:	0.2 - 20 torr

The significance of recombination and atom thermal conduction is confirmed, with radiation losses contributing greatly in the early afterglow. Electron loss by diffusion and wall recombination is small and the observed electron density gradient is due to diffusion of heat rather than of particles. Above 1 torr the incidence of molecular ion formation - especially significant in hydrogen - has also been included.

8) Numerical investigation of highly ionized helium plasmas
J.W.Long, A.A.Newton and M.C.Sexton
2nd Europhysics Study Conf.on Atomic and Molecular Physics of Ionized Gases, Innsbrück, Sept.1974, p.22.

The decay processes in a highly ionized helium plasma have also been studied numerically in one-dimensional cylindrical geometry for starting temperatures of the order 10,000 ^{o}K with gas pressures 20-500 mtorr and the same density range as for hydrogen. Experimental work had established that the decay is dominated by three-body collisional-radiative recombination in which the ionization energy is transferred to the electrons; subsequently this energy is lost by atom thermal conduction to the containing wall. The situation in helium is complicated by the possibility of recombination to one of the helium metastable states, in particular the $2^{3}S$ level. The helium plasma is assumed to contain electrons, neutral atoms, singly and doubly ionized ions. Radiative transfer is not considered but radiation loss processes are included. As for hydrogen, the main experimental decay parameters were confirmed especially the effect of the $2^{3}S$ metastables in maintaining elevated electron temperatures during the afterglow.

As referred to on p.4 of this report,the main plasma diagnostic has been the hydrogen cyanide (HCN) gas laser interferometer operating at 337 microns. This enabled electron densities up to approximately 5 x 10^{15} cm^{-3} to be readily monitored in the highly ionized plasmas.

In addition, as a result of direct contact with the French Commissariat a l'Energie Atomique, a special HCN laser system was designed and constructed for use as a diagnostic for thermonuclear machine plasmas.

Since 1975, attention has been concentrated in Cork on the laser/detector system itself. The laser was pulsed in the region of 10 kV, 10 - 100A to ascertain input powers suitable for optimum lasing and,in addition,the mean radial electron density (10^{11} - $10^{10}cm^{-3}$) during lasing was measured with an 8 mm microwave interferometer. (It will be noted that the pulse network and microwave equipment previously developed for the plasma afterglow work have now been adapted to monitor the laser plasma itself).

Mathematical models of the laser amplifying medium, i.e., the plasma,were formulated to calculate parameters such as preferred oscillation modes, mode compression near the critical density and onset of instability with particular reference to both radial and longitudinal electron density distributions. A comprehensive analysis is in course of preparation,but some preliminary results have already been presented in Europe and in the USA.

9) Gain and Visualization of the modes of a Thermally Stabilised HCN Laser
J.P.Lesieur, M.C.Sexton and D.Veron
J.Phys.D,Applied Physics, 5,1212,1972

Abstract: Optimization of a 337 μm HCN laser involving long-term stability,choice of beam splitter (polyethylene) and maximum power has been carried out. The gain determination leads to a value of 4% per metre. In addition, a liquid crystal camera has been designed to demonstrate visually the characteristics of several modes of the cavity.

Papers:

10) Mode characteristics of a pulsed HCN laser
A.Hamonic and M.C.Sexton
Proc.12th Int.Conf.on Ionization Phenomena in Gases, Eindhoven,August 1975,p.221.

Abstract: A study of the line emission from a pulsed HCN laser revealed a strong dependence on the repetition frequency which was attributed to the continuing presence of excited HCN molecules up to 20 milliseconds after the current pulse. An "inversion density" time-constant of approximately 2 milliseconds was deduced. Microwave measurements of the electron density ($\approx 10^{12}$ cm^{-3}) during the lasing action enhanced the explanation of the observed spectrum and demonstrated the existence of mode compression near the critical density.

11) Influence of the electron density on the modes of a pulsed submillimetre laser
A.Hamonic and M.C.Sexton
Bull.Am.Phys.Soc. 21,142,1976

Abstract: The line emission at 337μm from a pulsed HCN laser ($\approx$1 torr,5kV,25A for 25μsec) was monitored with pyroelectric detectors. Simultaneous electron density measurements during the lasing action were made with an 8 mm interferometer. Both the asymmetry of the line shape and cyclic variations in output power with pulse frequency strongly indicated the presence of excited HCN molecules up to 20 ms into the afterglow. Moreover, calculations taking radial electron distributions into account supported quantitatively the presence of mode compression near the critical density.

The availability of suitably fast detectors of submillimetre radiation is of paramount importance. Pyroelectric detectors have been successfully used in the present work. However,during 1975/76 a photoconductive detector/FET preamplifier unit at cryogenic temperatures was successfully developed in association with the Culham Laboratory. Both gallium doped and boron doped germanium crystals have recently been tested at 66 microns wavelength. Design criteria include (a) bandwidth up to 50 MHz approximately (b) noise reduction and minimization of external capacitances. This work is now nearing completion and will be fully reported in due course.

THESES (available on request)

Master of Engineering Science (National University of Ireland)

1) "A Plasma Radiometer for 115 GHz"
C.P.Downing (October 1971)

2) "A Microwave Investigation of Highly Ionized Plasmas"
P.J.Murphy (October 1973)

Doctorate in Philosophy (National University of Ireland)

1) "A Radiometric Investigation into the Variation of Electron Temperature in Deeply Modulated Plasma Columns"

D.M.Barry (October 1971)

2) "Laser Interferometric and Spectroscopic Study of a Highly Ionized Plasma"

J.H.Mountjoy (December 1972)

3) Docteur de Troisième Cycle (Université de Paris)

"Influence de la Densité Electronique sur les modes d'un laser HCN pulsé"
A.Hamonic (Juin 1975)